



Original Article

Thin-Plate-Type Embedded Ultrasonic Transducer Based on Magnetostriction for the Thickness Monitoring of the Secondary Piping System of a Nuclear Power Plant

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ABSTRACT

Pipe wall thinning in the secondary piping system of a nuclear power plant is currently a major problem that typically affects the safety and reliability of the nuclear power plant directly. Regular in-service inspections are carried out to manage the piping system only during the overhaul. Online thickness monitoring is necessary to avoid abrupt breakage due to wall thinning. To this end, a transducer that can withstand a high-temperature environment and should be installed under the insulation layer. We propose a thin plate type of embedded ultrasonic transducer based on magnetostriction. The transducer was designed and fabricated to measure the thickness of a pipe under a high-temperature condition. A number of experimental results confirmed the validity of the present transducer.

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1. Introduction

Wall thinning of a secondary piping system is a critical issue related to the safety of nuclear power plants (NPPs). This condition can even lead to fatalities when, for instance, the main feed-water pump has an elbow rupture, as occurred in the Surry Unit 2 in the USA or when the condensate system has a straight pipe rupture, such as in Mihama Unit 3 in Japan [1].

Accordingly, a secondary pipe with a thin wall must be supervised under careful control. This is mainly managed with thickness measurements using ultrasonic waves. However, the secondary pipe has various thicknesses and shapes, and it is typically too long to be inspected. Furthermore, most of the pipe is covered with heat-insulating material that must be removed before ultrasonic testing can be performed. This makes inspections difficult to carry out during the operation of

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the NPP. Generally, during the overhaul of an NPP, ultrasonic nondestructive testing is conducted to measure the thickness of pipes. All NPPs have management plans specific to pipe wall thinning [2–4], and the target objects to be managed in the thousands or more. In-service inspection tasks should be done during the overhaul roughly every 18 months. Regular monitoring is necessary when the pipe becomes thinner than a certain standard. Thus, online thickness monitoring techniques are required to determine the progress of wall thinning.

During the operation of the plant, the working temperature of the secondary piping system can reach as high as 300°C. Consequently, conventional ultrasonic transducers cannot be applied due to their low working temperature range. As a result, a new transducer capable of withstanding a high-temperature environment is necessary. In an effort to develop such a device, various studies of high-temperature transducers [5–7] and methods that use a waveguide to avoid direct contact with the heat-affected zone [8–14] have been proposed. Among them, Nisbet [8] reported a water or liquid waveguide for thickness measurements in the roles of both a couplant and a coolant. Cegla et al [9–11] reported a crack and wall thickness monitoring method that uses shear horizontal (SH) waves with dry-coupled waveguide transducers. Hernandez-Valle and Dixon [12,13] reported the design and testing of a high-temperature electromagnetic acoustic transducer with a pulsed electromagnet. Ashish et al [14] reported a rod-type magnetostrictive transducer (MsT) for in-situ inspections with a longitudinal wave.

An insulation layer covers numerous pipes to protect them and to retain heat. In this situation, a transducer installable under the layer is necessary for structural health monitoring. Such a transducer must be very thin to be embedded between the surface of a pipe and its insulation layer. Waveguide transducers are not appropriate in such a case because of installation problems.

In this study, we propose a thin-plate-type transducer that satisfies the requirement of install ability under the insulating layer in the secondary piping system of a NPP. The proposed transducer can be applied in a high-temperature condition, and it was fabricated based on magnetostriction fundamentals for a very thin shape. Magnetostriction refers to the coupling phenomenon between a magnetic field and mechanical deformation. Ultrasonic waves then can be generated and measured using this principle. This phenomenon occurs in a ferromagnetic material and its alloys. The magnetostriction disappears beyond the Curie temperature of the material [15]. Iron–cobalt (FeCo) alloy, used in this work, can be sufficiently applied to a temperature of approximately 300°C, the maximum operating temperature of a secondary piping system, as its Curie temperature reaches nearly 940°C [16]. Generally, an MsT is composed of a magnetostrictive material, a coil, and a magnet. The coil and the magnet can be manufactured to endure a high-temperature condition.

Very thin plate-type transducers can be fabricated because the FeCo alloy can be formed with a thickness of 0.15 mm in this work. The coil and the magnet can also have a thin form. Hence, each component of the transducer is designed to be thin to measure the pipe thickness. To design the transducer, an analysis model was initially established for an acoustic

field analysis, after which the layout of the coil was devised. Finally, a prototype transducer was fabricated to a thickness of approximately 3 mm. Subsequently, several tests were conducted to verify the transducer, during which the high-temperature characteristics of the transducer were assessed. In the experiment, we observed the effect of the bias magnetic field of the transducer. Eventually, the fabricated prototype transducer was tested in a performance evaluation for high-temperature conditions and to determine the wall thickness. The transducer showed sufficient performance to detect them. In conclusion, for this study we developed a thin-plate-type MsT that can be embedded between the surface of a pipe and its insulation layer. This permanently installable transducer will be a useful tool for monitoring the wall thicknesses of pipes in the high-temperature environments of secondary piping systems of NPPs.

2. Design and fabrication of the thin-plate-type embedded MsT

2.1. Principle of the MsT

An MsT can generate and detect ultrasonic waves based on the magnetostrictive effect [17]. The effect denotes a relationship between material deformation and magnetic field induction. Thus, an MsT is only applicable to a ferromagnetic material and its alloys. Typically, the MsT is comprised of magnetostrictive patches, actuating and sensing coils, and permanent magnets (or electromagnets). These components should be deployed to transduce specific ultrasonic waves.

Fig. 1 depicts the patch-type MsT. It can easily transmit and receive SH waves in this arrangement [16]. It also operates via the magnetostriction of the ferromagnetic patch materials. An MsT uses actuating and sensing coils to create a dynamic magnetic field and permanent magnets to produce static magnetic field. The cross combination of these magnetic fields can be converted to the shear deformation of the patch. Hence, SH waves are propagated on the patch and the waves are conducted from the patch to direct-coupled materials.

A patch-type MsT usually has higher sensitivity than a noncontact-type MsT, because a magnetostrictive patch is mechanically coupled to the structure and the material of the patch deforms better than a general ferromagnetic

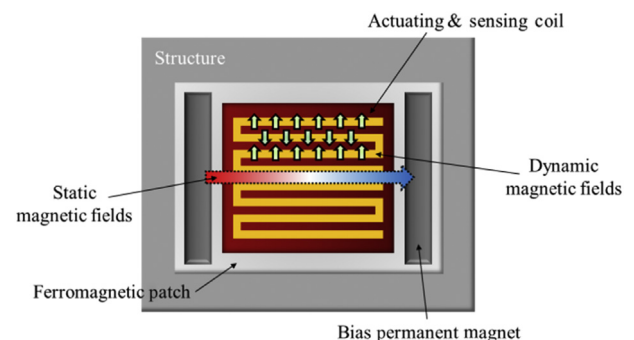


Fig. 1 – Schematic of the magnetostrictive transducer utilizing shear horizontal waves.

Fig. 4 – Analysis model of the acoustic field of a shear horizontal bulk wave.

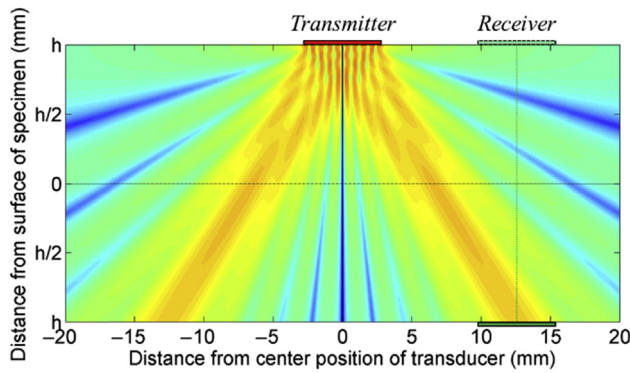


Fig. 5 – Calculated acoustic field of the proposed coil with five fingers ($f = 5$ MHz, $d = 0.6$ mm, $h = 10$ mm).

maximum permissible temperatures are 350°C and 450–550°C, respectively. With regard to the magnetic properties, SmCo magnets are better than alnico magnets.

FeCo alloy is one of best magnetostrictive materials, with a higher, and proper, Curie temperature of 940°C. This material is appropriate for the temperature range of this study. The amplitude of an SH wave on a FeCo alloy patch under a high-temperature condition was checked and compared with those of neodymium, SmCo, and alnico magnets [16]. The magnetostriction was acceptable at 300°C in both the SmCo and alnico magnets. However, the amplitude with the neodymium magnets collapsed at 250°C.

We found that SmCo or alnico permanent magnets can create a bias magnetic field at the temperature range up to 300°C and an FeCo alloy patch can deform enough to transduce an SH wave efficiently. Magnetostriction depends heavily on the bias magnetic field; thus, we studied changes in the bias magnetic field due to temperature variations in detail and attempted to determine a proper and optimal magnetic field in the target condition.

Fig. 7 shows a schematic of the experimental setup used to test the high-temperature characteristics of the TEMT. Current from a DC power supply can enable an electromagnet to produce a bias magnetic field. SH waves on an FeCo alloy patch are measured to observe the magnetostrictive deformation behavior. A sine burst wave of two cycles is transmitted and received in the pulse-echo method. Fig. 8 shows the measured signal of the SH wave, where V_{pp} is the difference between the values of the maximum and minimum amplitudes of the measured SH wave. The repeatability was checked and the hysteresis was verified to confirm uniform conversion efficiency.

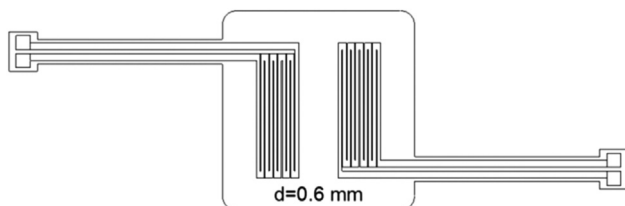


Fig. 6 – Design drawing of the meander coil on a flexible printed circuit board.

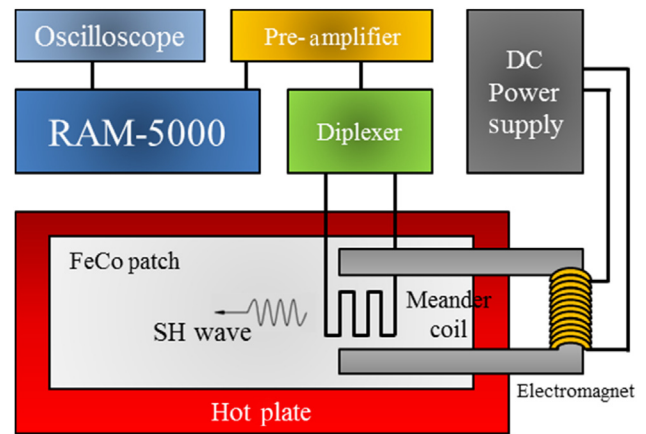


Fig. 7 – Experimental arrangement used to test the high-temperature characteristics of a thin-plate-type embedded magnetostrictive transducer.

The SH wave measurements were taken under an elevated electric current for different temperature conditions. Fig. 9A shows the characteristics of the bias magnetic fields for each temperature condition. With a condition of the electric current of approximately 230 mA, V_{pp} showed the highest result. With current lower than 230 mA, V_{pp} increases rapidly. By contrast, V_{pp} decreases steadily when current higher than 230 mA is transmitted. In this case, good performance was noted under a low magnetic field. These results indicate that small magnets can be applied in this work because there is no need for high magnetic fields. Fig. 9B shows the conversion efficiency of an SH wave with the present measurements at an elevated temperature. The amplitudes at 200°C, 300°C, and 400°C declined by 3%, 11%, and 24%, respectively. Thus, the signal measurements under a high-temperature condition were reasonable.

2.4. Fabrication of a TEMT

There are several considerations when fabricating a TEMT. Most importantly, the transducer performance should be

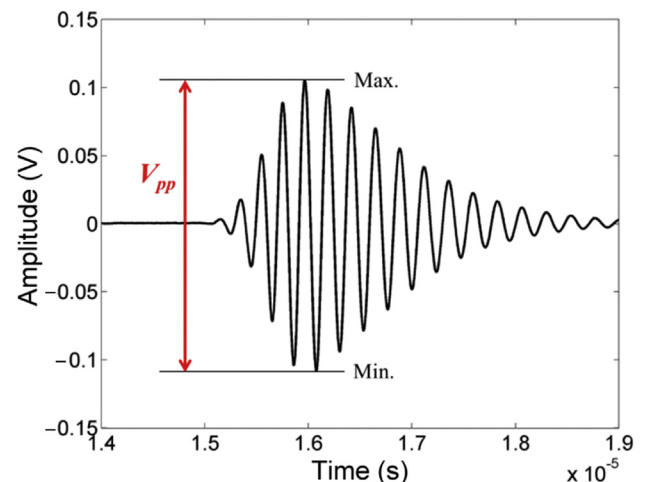


Fig. 8 – Measured shear horizontal wave propagating through a FeCo alloy patch.

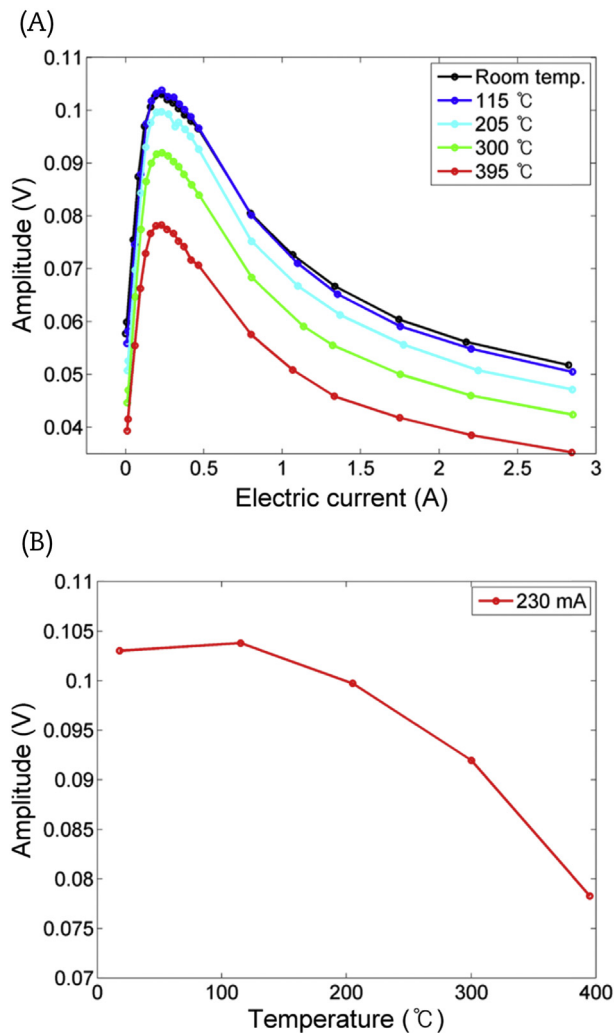


Fig. 9 – Amplitude of the measured SH waves. (A) under the varied bias magnetic field, and (B) under the varied temperature.

stable under general circumstances and under high-temperature conditions. Therefore, the selection of transducer components is very important because these components will strongly influence the sensitivity and performance of the transducer. In this study, we considered applicable and durable parts of a TEMT.

A FeCo alloy patch (Hiperco 50 HS) was selected as the magnetostrictive patch in this study. It is composed of 0.01% carbon, 0.05% manganese, 0.05% silicon, 0.30% columbium/niobium, 1.90% vanadium, and 48.75% cobalt. For the best performance of bias magnetic field in high-temperature condition, SmCo permanent magnets were used. The FPCB type of meander coil was used and the thickness of the coil is approximately 0.1 mm. This thin film coil can endure temperatures as high as 300 °C. However, deformation of the coil can occur due to temperature variations. Accordingly, precautions such as transducer molding are required to fix the coil. To apply at higher temperatures, it may need a ceramic bobbin and a coil-protecting tube. An asbestos tube was used, as it can protect the wire from the heat. Long-term heat

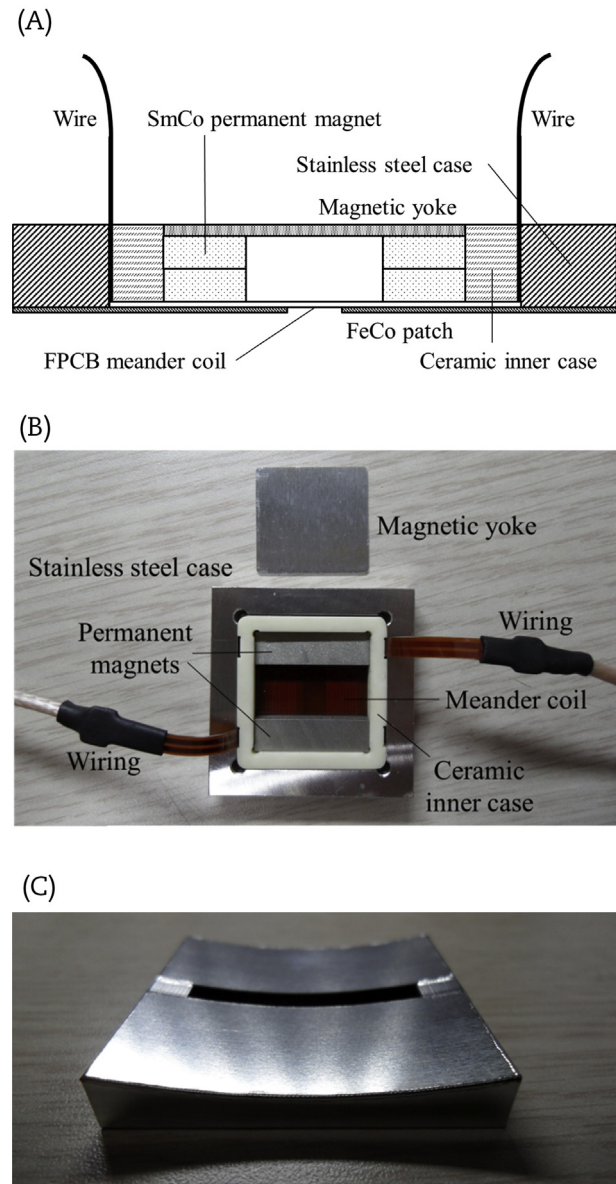


Fig. 10 – Design and fabrication of a thin-plate-type embedded magnetostrictive transducer (TEMT). (A) Schematic of a TEMT. (B) A prototype TEMT and its components. (C) A curved TEMT as a pipe specimen.

exposure causes the tube to crumble when rubbing it by hand. However, the wire shape is retained. Thermocouple wire is another possibility, but its resistance is much higher than those of other wires. As a result, impedance matching between the transducer and equipment can be challenging, but it is not impossible. A soft soldering material (Speedsol, resin core solder) was also used. Its solidus temperature is approximately 295 °C. In addition, it seldom melts at temperatures up to 400 °C. A general brazing filler metal (Shin Young Metal BAg-2) with a solidus temperature of 605 °C was also prepared as a backup. However, a brazing method cannot be applied to an FPCB because the torch can melt the thin film. A special coil design is necessary when using the brazing method. To attach a TEMT onto a metallic structure, high temperature glue is needed. Two adhesives were selected for

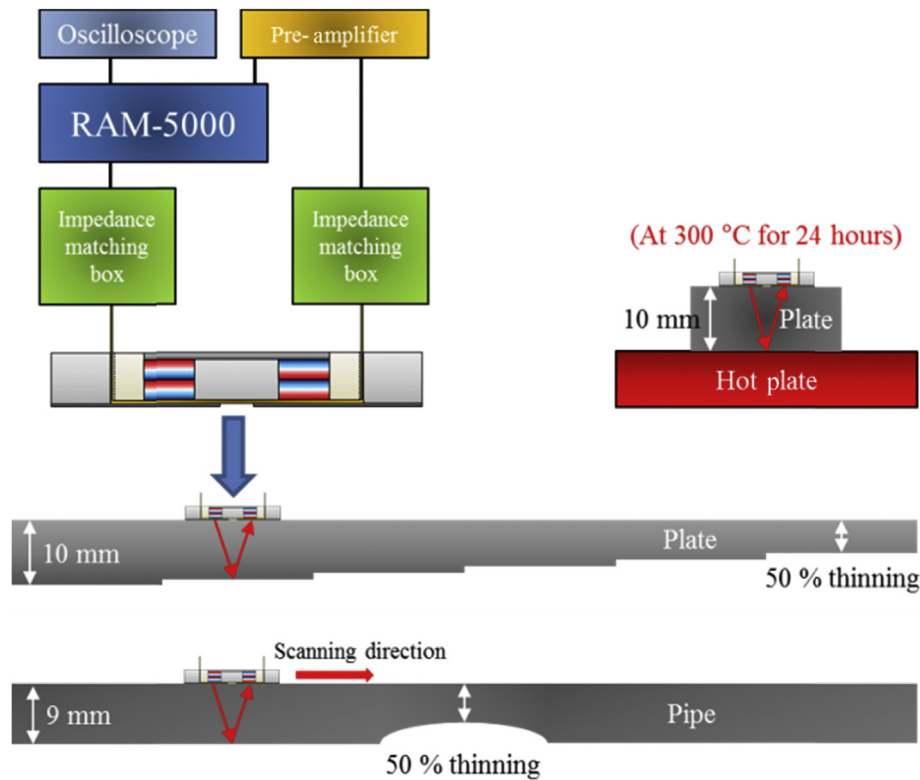


Fig. 11 – Experimental setup of thickness measurement test using the thin-plate-type embedded magnetostrictive transducer.

use here: J-B Weld Steel Reinforced Epoxy ($< 315^{\circ}\text{C}$) and Are-mco Ceramabond 571-L/P ($< 1,760^{\circ}\text{C}$).

Fig. 10A shows a schematic of the prototype TEMT. Fig. 10B is a photograph of the fabricated prototype TEMT and its components. Two FeCo alloy patches are welded onto a metal case of KS-ST304 (stainless steel). These two patches are used to transmit and receive the part that reduces the direct surface wave. These welded patches transform properly. The ceramic inner case prevents deformation of the coil and fixes all components inside the TEMT. The thickness of the TEMT was approximately 3 mm in this work. Reducing the size of the magnets can make the transducer much smaller and thinner. Fig. 10C shows a curved TEMT applicable to a pipe specimen with a specific curvature.

3. Thickness measurement tests using a TEMT

After the TEMT was fabricated, three types of experiments were conducted. Fig. 11 shows the experimental setup of these tests to measure the thickness of the plate and pipe specimen. Preliminarily, we attempted to evaluate the high-temperature performance of the TEMT. A carbon steel plate 10 mm thick was inspected and the transducer was attached onto the specimen using ceramic epoxy (Aremco) and metal reinforced epoxy (J-B Weld). Figs. 12A and 12B show the measured raw signal of an SH bulk wave with the ceramic epoxy attached to the TEMT at room temperature and at 300°C , respectively. The amplitude is decreased by 50% and arrival time is increased by

nearly 4%. We confirmed that the temperature affected the TEMT, but the signal itself at 300°C did not change after 24 hours. Fig. 12C shows the raw signal of the SH bulk wave measured by the metal-reinforced epoxied TEMT at 300°C . The amplitude is only 10% of that of the ceramic epoxy. However, the signal is better than the ceramic epoxy according to the results of a signal analysis. The metal-reinforced epoxy is restricted in terms of its workable temperature, which is $< 315^{\circ}\text{C}$.

Subsequently, to evaluate the performance of the TEMT as a thickness gauge, we prepared two types of carbon steel specimens. A stepped specimen with thickness variations (thicknesses of 10 mm, 9 mm, 8 mm, 7 mm, 6 mm, and 5 mm) and a thin-walled pipe of 9 mm thickness were utilized. Among them, Fig. 13 shows first arrival time variation of the SH bulk wave due to the change in the of plate wall thinning. All first arrival times of SH bulk waves were determined by the peak selection of the wave. From these result, the first arrival time is shortened when the thickness decreases. In short, we confirmed that the TEMT can measure the thickness of plates. Accordingly, we studied the performance of a TEMT to detect pipe wall thinning. Fig. 14 shows the measured thickness of thin-walled pipe according to the scanning method. The total length of the thin pipe wall was about 90 mm, and the thickness of the center position is approximately 4.5 mm (50% wall loss). In this result, there are a few errors with regard to the measured thickness. However, some measured points are quite precise, and the result shows a well-fitted thickness profile.

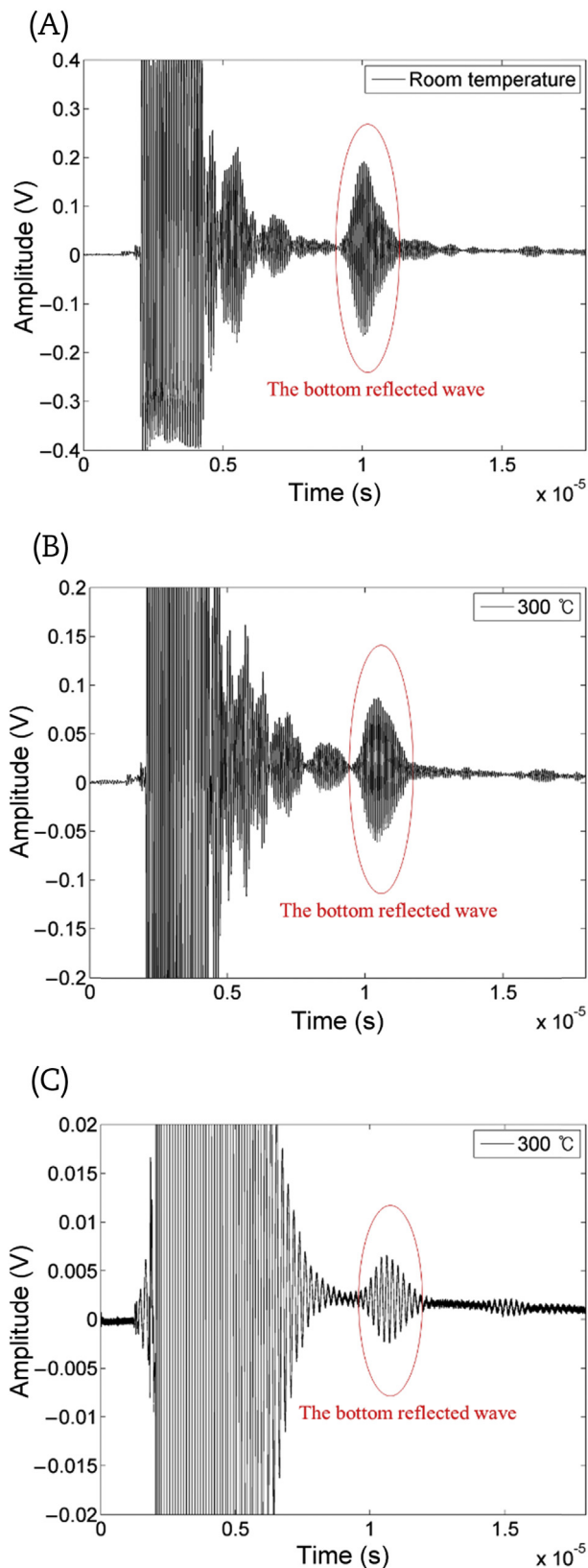


Fig. 12 – Raw signal of shear horizontal bulk wave. (A) Ceramic epoxy attached thin-plate-type embedded magnetostrictive transducer (TEMT) at room temperature. (B) Ceramic epoxy attached TEMT at 300 °C. (C) Metal reinforced epoxy attached TEMT at 300 °C after 24 hours.

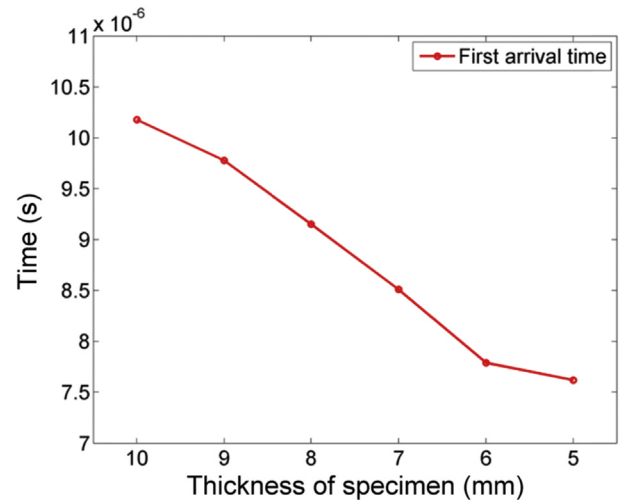


Fig. 13 – First arrival time variation of shear horizontal bulk wave due to thickness change of plate wall thinning.

4. Discussion

In this work, a thin-plate type of an ultrasonic transducer based on magnetostriction was proposed and developed to monitor the thickness of NPP secondary piping systems in high-temperature environments. To do this, two requirements were considered and duly weighed. First, the transducer should be able to be inserted between a pipe and the pipe insulation. Thus, it has to be thin. The proposed transducer can satisfy the requirements because a thin MsT can easily be made. Second, the transducer must be able to withstand a high-temperature condition. Hence, the selected components of the proposed transducer were those that could tolerate such a condition.

All things considered, the design was established and the transducer was fabricated and tested. A coil 5 MHz (diameter = 0.6 mm) in size with five fingers was determined and the optimum receiving distance was set to 12 mm. The

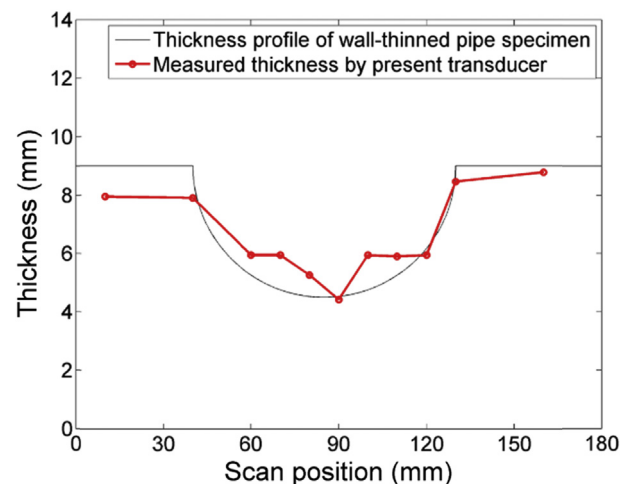


Fig. 14 – Measured thickness of a thin-walled pipe by the scanning method.

bias magnetic field was checked, and it was found to decrease by 11% at 300°C. For the fabrication of the transducer, a FeCo alloy patch, an SmCo permanent magnet, and a high-temperature epoxy adhesive were selected. Finally, we developed the transducer with a thickness of about 3 mm and termed it a TEMT. The amplitude of an SH bulk wave transduced by the TEMT was decreased by about 50%. However, the amplitude was retained for more than 24 hours. Finally, thickness gauges for a thin-walled plate and pipe were completed, and the results with these represented well-fitted thickness measurements. For future work, to quantify the thickness data, several measurements and databases will be essential. The TEMT should also be improved, especially with a new design that reduces the deformation of the coil. Lastly, to prove the durability of the TEMT, sufficient testing for a long period in a high-temperature environment will be necessary.

Conflicts of interest

All authors have no conflicts of interest to declare.

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